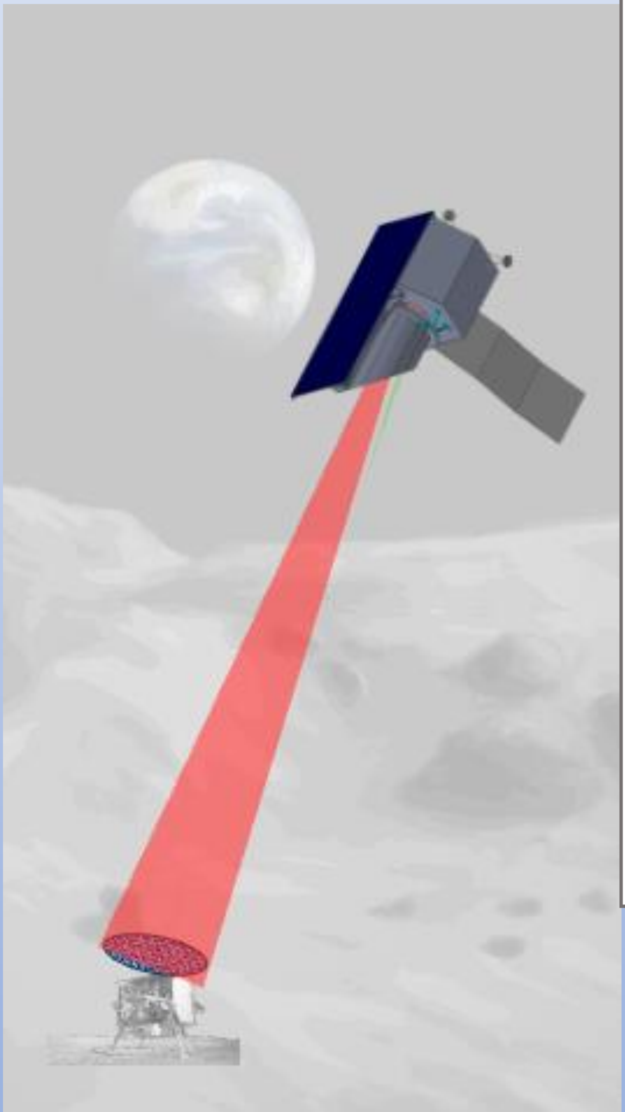

Long lunar nights limit science lander lifetimes to only two weeks unless they carry large batteries or radioisotopes: An orbiting beamed power spacecraft is another option to provide this energy.

Power Beaming From Lunar Orbit to Small Lunar Science Assets

Derived from a Compass Concept Study, 9/2023

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Abstract

Long lunar nights limit science lander lifetimes to only two weeks in most global locations unless they carry large batteries or radioisotopes. An orbiting beamed power spacecraft is another option to provide this energy, thus removing the energy storage burden on the lander while still giving it years of science operations.

The Problem

The moon is of great importance due to its proximity, unique science and potential uses for humanity. Indeed, the unique science to be gathered on the moon is not limited to its poles, where water is sought. These basic science questions about the moon include: its origin (and how it relates to the Earth), seismic activity (and its view to the moon's interior), its tidal lock to Earth, and past volcanoes [1]. Being so close to Earth should make science landers simple to operate and communicate with once landing can be achieved. Unfortunately, the moon is tidally locked with the Earth so that not only is one side never seen from Earth, but the surface systems must endure roughly two weeks of night out of every month that the moon orbits the Earth. While there are some locations on ridges on the pole which could have longer solar illumination, these are few and usually only occur during lunar summer [2]. These two weeks of night will require surface assets to either use radioisotope heaters or very large batteries to survive the 354 hr night with its 60 K temperatures. Without these solutions the landed assets are limited to a single, no-greater-than two-week science period, greatly reducing the potential science return while still requiring systems to land and operate on the moon.

Currently, radioisotope production is limited to a few kilograms per year and is mainly earmarked for deep space science missions. Cost overheads for such systems are not insignificant. Alternatively, the battery solution can be quite heavy, requiring more mass than the science system itself. A recent study showed that roughly 5 kg of landed mass are needed for every watt of power required by the science payload in shadow, whether electrical power for operations or heat to survive the night [3]. Such a battery powered system would also greatly increase the cost of landing the payload, with published costs by Astrobotic at $1.2 M/kg to the lunar surface [4]. Alternatively, delivery costs are only $0.3 M/kg to place payloads in lunar orbit -perhaps there is an orbital way to service landed science assets.

Lunar Beamed Power Concept

Beaming power from orbit has been suggested for the moon by a few authors but with no real evaluation of the beamcraft [5, 6]. By using a specially tuned photovoltaic (PV) array on a science lander (that also works with sunlight) the mass and cost overhead of large batteries or radioisotopes can be eliminated. Instead, a laser 'beamcraft' can gather solar power every orbit and distribute it to several landers on the dark side (or inside a permanently shadowed region at the poles). While the end-to-end efficiency of the laser beam system is around 10%, the more frequent availability of sunlight in orbit and the cost savings in putting the power system in orbit instead of on the surface could make it competitive.

The beamcraft operates by gathering energy with solar arrays while in sunlight, stores the energy in an on-board battery, and then powers a laser beam which is then directed at the customer lander. A large aperture, stable and accurately pointed optic or 'telescope' is needed to focus the beam to the size of a few meters diameter to a laser tuned PV array which converts the laser light back into electricity which is used to charge the landed asset battery to allow continued operations until the next beamcraft pass.

Lunar Beamed Power Case Study

A case study was performed by the NASA Compass concurrent engineering team to explore how such a system might operate, to identify operational and technology challenges and to perform a first-order cost trade with nighttime battery powered landers. This study is only one possible solution.

The case study assumed use in the 2030s and eighteen, equally and globally distributed science landers requiring 50 W during nighttime operations (the 50 W included waste heat and electric heaters sufficient to keep the payload and support equipment warm). The previous sample overnight landers that required large batteries were re-evaluated to have just a 12 hr battery instead of the 354 hr battery.

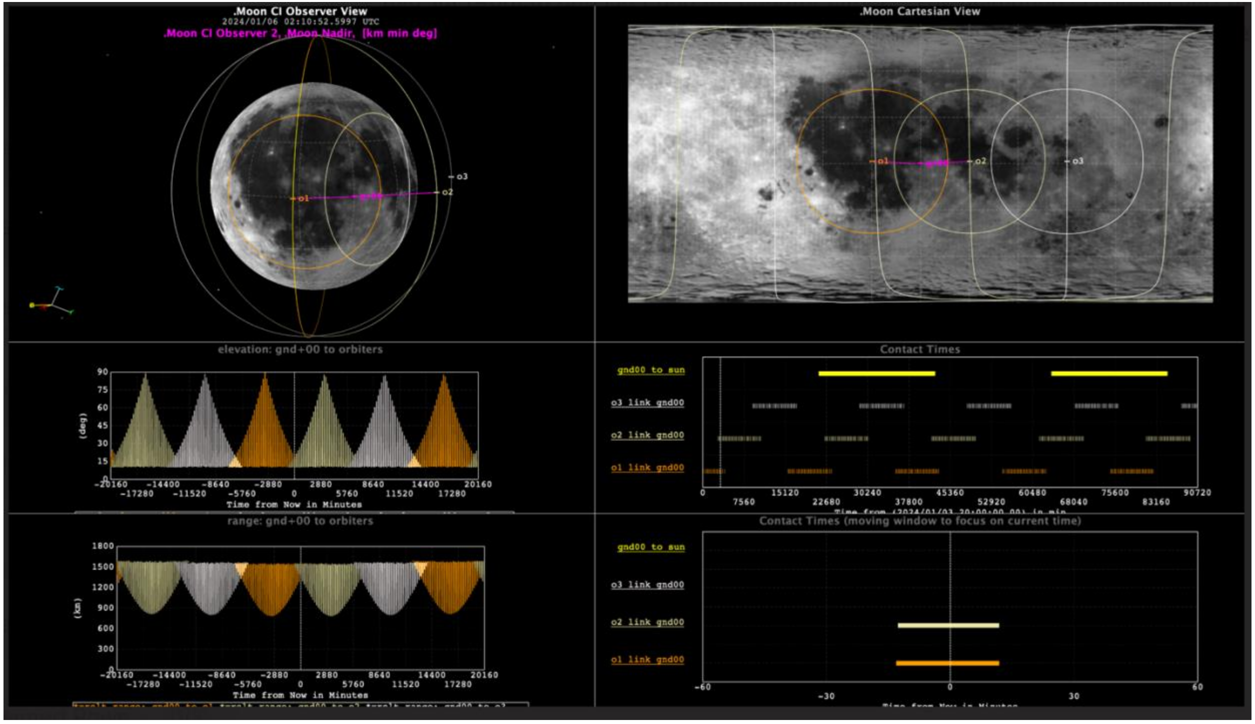


Figure 1: SOAP Analysis of Beamcraft Coverage of Equatorial Surface Assets

Lunar Coverage

Since the moon is tidally locked, a three beamcraft constellation at 800 km, each in a polar orbit, separated in right ascension by 60° was chosen to provide global coverage for at least 24 minutes out of every 3 hrs. The 800 km altitude was chosen as a compromise between lunar coverage and distance to users. Figure 1 shows the three beamcraft coverage for the driving case of equatorial lander customers, since the polar orbits provide increasingly improved surface coverage with latitude. A single equatorial lander is shown in Figure 1 to prove the constant coverage. Eighteen landers could be supported, with half of them in shadow at any given time. It is known that orbits around the moon can be impacted by mass concentrations on the moon and the perturbations from the sun but that there are ‘frozen orbits’ whose parameters change little over time but oscillate [7]. The 800 km polar orbits were evaluated over 10 years of operations, and while some parameters did move, all the orbits drifted with the same relative bias ensuring recurring coverage of the landers.

Concept of Operations

The use case concept of operations is shown in Figure 2. Each beamcraft would energize three shadowed landers each orbit. Thus, nine shadowed landers could be charged. It was decided to add a relay function to the beamcraft to provide data return and thus provide a link to the lunar farside as well as make the return link easier on the near side. The relay link can return around 1.8 GB of data from each user, each day to the Earth (i.e. 32 GB of data from the 18 landers each day). The relay link would also double as a connection between the beamcraft and the lander to center and maintain the 3 m diameter laser spot on the lander PV array. Each beamcraft charges their assigned landers for 15 minutes each during each orbit. The beamcraft charges its batteries when in sunlight and providing daytime relay. At the poles, the beamcraft could charge and beam power simultaneously. (Seasonally, the beamcraft will encounter an orbit perpendicular to the sun when it is constantly illuminated, similar to LRO.)

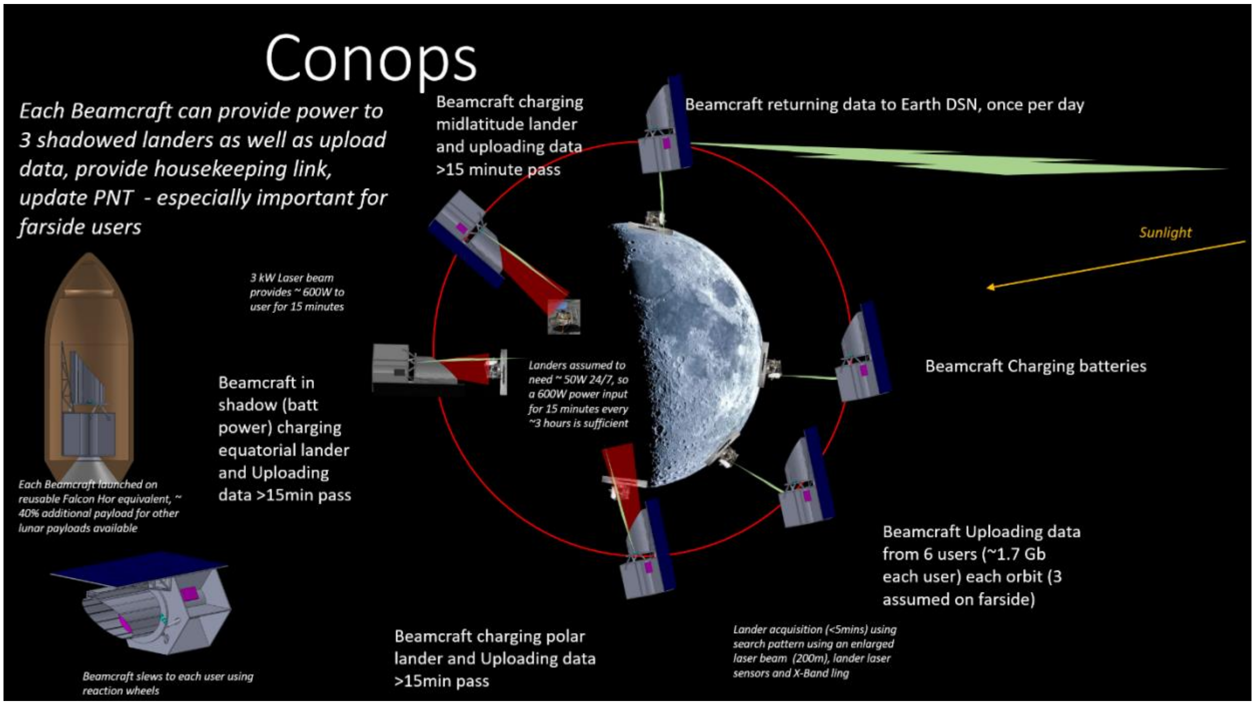


Figure 2: Use Case Concept of Operations

Power Link: The power link from the beamcraft to the lander has several steps. First the beamcraft will make an X-band communications link with the lander. The beamcraft will know the landers position to less than 1 km based on LRO surface image data. The beamcraft would then activate and defocus its beam to a 200 m spot and begin the search process, locking onto the lander when the lander PV sensors detect the beam and return the information to the beamcraft through the X-Band link. Once locked the beam is refocused to a very small 3 m diameter spot. Nine minutes have been allotted to this search and lock but it could be shorter. Fifteen minutes of power transfer is made as the beam craft slews to continuously point the beam at the lander. A 1.6 m PV array (tuned to the 1.07 micron laser, but also able to receive sunlight [8]) on the lander is pointed to the beamcraft as it orbits overhead. The power path has many steps but the main efficiency losses are a 38% efficient laser and 50% efficient lander PV cells (in the laser wavelength). The lander will need about 640 W of power for the 15-minute pass to charge the batteries which will then power the lander at 50 W over the next few hours until the next pass. The required beamcraft laser input power is 7600 W. The resulting ~10% end to end efficiency, while low, can still be competitive when compared with large landed batteries as discussed earlier.

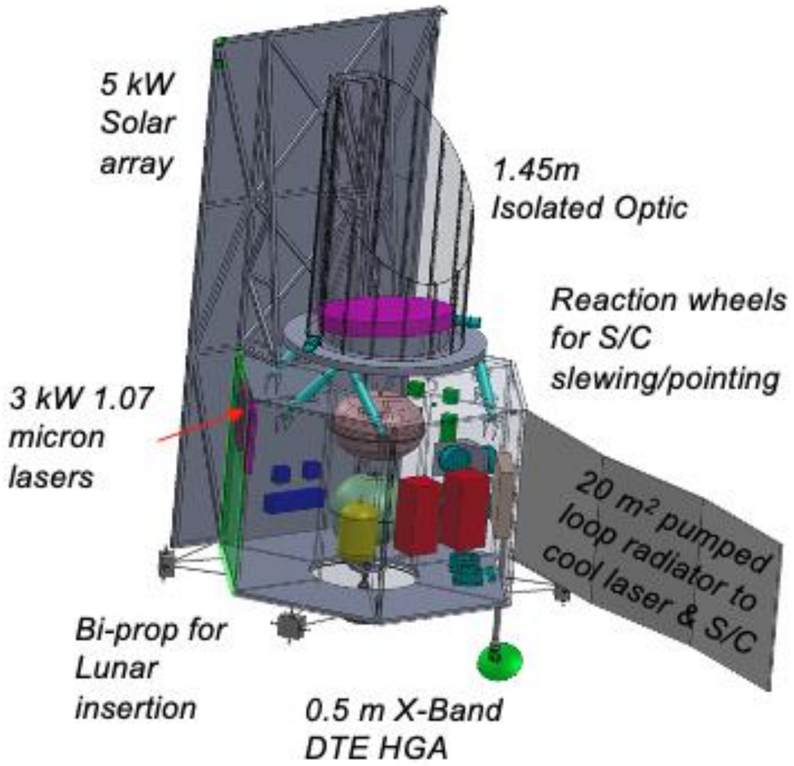


Figure 3: Lunar Beamcraft with Key Elements Highlighted

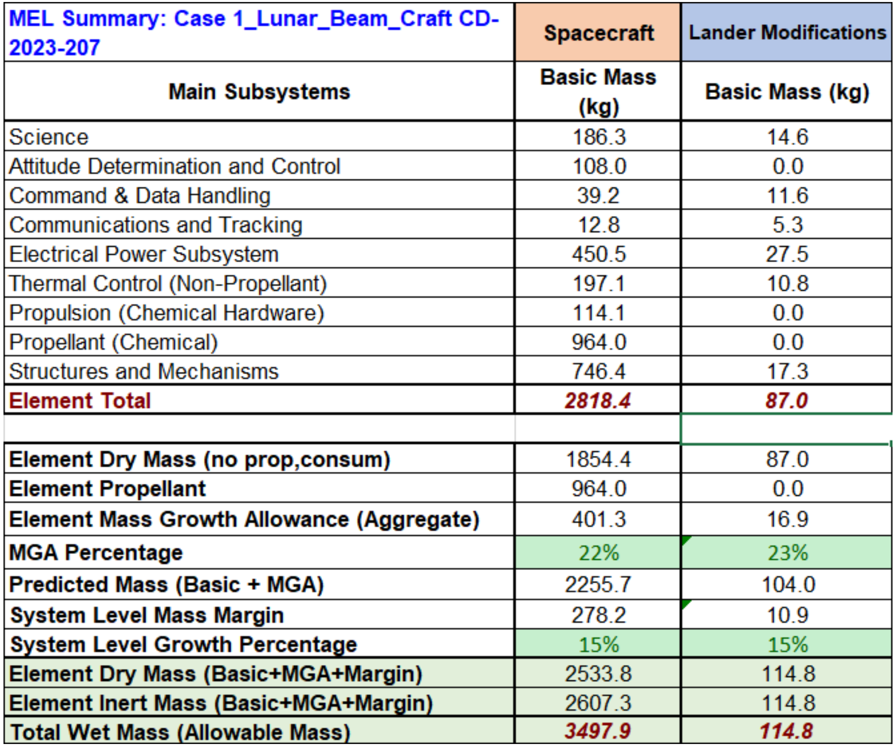
Beamcraft Concept Design

The beamcraft design combines many existing spacecraft technologies with a few new ones. A graphic of the beamcraft is shown in Figure 3. The heart of the system is a 3 kW laser (output) which is based upon representative terrestrial fiber lasers [9]. This laser will be cooled with a pumped loop through a deployed radiator. The laser beam focusing utilized a 1.45 m optical ‘telescope’ based upon the successful Kepler telescope. This will provide the required 3 m spot at 1500 km. Pointing for the beamcraft, while challenging, has been demonstrated by Kepler and other space telescopes to the sub microradian requirements by using reaction wheels and isolating the optics from the rest of the spacecraft [10]. Adding the requirement to point this accurately while slewing as the beamcraft flies over will be a challenge. The rest of the spacecraft is based upon off the shelf systems such as a fixed 5 kW solar array (to keep the bus 'quiet' for the optics), the Li-ion batteries to be charged by the solar array and discharged to power the 7.6 kW input laser, and the bipropellant system to insert the beamcraft into its orbit and deorbit it at end of life. The beamcraft is roughly 3 m in diameter and 6 m tall when stowed. It was found to fit into a Falcon Heavy reusable 5 m fairing with about 40% leftover payload mass for additional lunar payloads. A top-level mass breakdown is shown in Table 1.

Science Lander Modifications

Table 1 also shows the estimated mass of the modifications to the lander payload to allow overnight operations using the beamcraft. A comparative design with a large thermal vault and batteries required 280 kg to survive the night. This heavier, all-battery design would require a much larger lander, while the beamcraft supported design could stay on the ~100 kg CLPS landers to be flown soon. The key technologies will be use of PV cells tuned to the 1.07 micron laser for the lander receiving array as well as integrating the cells to address the differences in power from a laser beam with a gaussian distribution. Pointing requirements might require a small laser beacon from the lander to direct the Beamcraft power beam.

Table 1: Mass Breakdown on the Beamcraft (Spacecraft) and the Lander Modifications Required to Make Use of the System (Lander Modifications)



MEL Summary: Case 1_Lunar_Beam_Craft CD-2023-207	Spacecraft	Lander Modifications
Main Subsystems	**Basic Mass (kg)**	**Basic Mass (kg)**
Science	186.3	14.6
Attitude Determination and Control	108.0	0.0
Command & Data Handling	39.2	11.6
Communications and Tracking	12.8	5.3
Electrical Power Subsystem	450.5	27.5
Thermal Control (Non-Propellant)	197.1	10.8
Propulsion (Chemical Hardware)	114.1	0.0
Propellant (Chemical)	964.0	0.0
Structures and Mechanisms	746.4	17.3
Element Total	***2818.4***	***87.0***
Element Dry Mass (no prop,consum)	1854.4	87.0
Element Propellant	964.0	0.0
Element Mass Growth Allowance (Aggregate)	401.3	16.9
MGA Percentage	22%	23%
Predicted Mass (Basic + MGA)	2255.7	104.0
System Level Mass Margin	278.2	10.9
System Level Growth Percentage	15%	15%
Element Dry Mass (Basic+MGA+Margin)	2533.8	114.8
Element Inert Mass (Basic+MGA+Margin)	2607.3	114.8
Total Wet Mass (Allowable Mass)	***3497.9***	***114.8***

Cost Comparison

When estimated, the three beamcraft (with launch) came to a point estimate cost of $2 billion (FY24), not including technology development costs (anything below TRL6). The three beamcraft constellation would service 18 lunar landers.

Current commercial offerings, such as those by Astrobotic, quote a delivery cost of $1.2 M/kg for payloads to the lunar surface. These services do not encompass provisions for overnight power or farside communications relay. A study conducted for the CLPS 'Survive the Night' workshop detailed the requirements for a lander to sustain a 40 W power level through the lunar night, necessitating approximately 280 kg of support mass for energy storage, insulation, accommodation, and added solar array to recharge the overnight batteries. If powered by the beamcraft, the lander's batteries are minimal and a pointable photovoltaic array is added, for an aggregate payload mass of 115 kg. This represents a mass savings of 165 kg per lander.

In a nominal scenario where 18 lunar science landers, each with a five-year mission duration, require landed support, the conventional heavy battery approach would necessitate approximately $6 B for support mass and $1.3 B for relay support, *totaling $7.3 B for night power and relay infrastructure*. The alternative beamcraft approach would require around $2 B for the deployment of the three beamcraft and an estimated $2.5 B for the landed support mass, culminating in a *total of $4.5 B for equivalent night power and relay capabilities.*

These analyses suggest that the adoption of beamcraft could be more than competitive with large landers with overnight batteries as long as one is willing to invest in the beamcraft infrastructure.

Conclusions

Powering science landers through a fourteen-day lunar night is challenging but would allow years of science instead of just two weeks. Beaming power using a laser beamcraft in lunar orbit adds an additional power option for multiple landed science assets dispersed globally. Providing cabling across the lunar globe would require significant infrastructure and deployment. Radioisotope systems provide both power and heat and would be a great option if the current Pu238 production could be increased sufficiently or alternative radioisotopes brought online. Adding large battery packs requires no new technologies but would require each science lander use a much bigger lander and launcher. Powering global science landers by beaming the power from lunar orbit seems to be a feasible solution which could save costs compared to larger landers. A case study showed that ten users or more might make the beamcraft cost effective. That number only improves if a data relay function is added to the beamcraft to support far side users. More definition is needed for the beamcraft concept including the challenges of integrating kW-class lasers with a spacecraft, accessing and precisely pointing to landers, and PV arrays that can receive a gaussian laser light beam and still perform well in sunlight.

While power beaming for small lunar landers might be competitive, scaling the concept up for large users (crew and ISRU) might not make sense, especially when dedicated power systems such as reactors could be placed nearby. The concept presented here should roughly scale linearly so that if a user needed, say 1 kW during the lunar night, the beamcraft would need to have a 60 kW laser and probably over 100 kW of power. For a 10 kW user the beamcraft would be quite large with a 600 kW laser needed and over 1MW of power.

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